Progress Report (DR-3)

July thru Sept. 1990

SPACE TRANSPORTATION ENGINE PROGRAM (STEP)
PHASE B
CONTRACT NAS8-38160

Prepared For :
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared by:

ALS Project Engineering

Approved By:

A. H. Weiss

Program Manager

Rockwell International
Rocketdyne Division
6633 Canoga Avenue
Canoga Park, CA 91303

FOREWORD

This progress report is submitted to the NASA Marshall Space Flight Center, Huntsville, Alabama, by the Rocketdyne Division of Rockwell International, Canoga Park, California. This submittal is in compliance with the Space Transportation Engine Program (STEP) (NAS8-38160) Contract Data Requirement No. 3, Progress Report. The report contains a summary of technical progress, and a description of technical or programmatic issues.

ABSTRACT

The Space Transportation Engine Program (STEP) Phase B effort includes preliminary design and activities plan preparation that will allow smooth and timely transition into a Prototype Phase and then into Phases C, D & E. A Concurrent Engineering approach using Total Quality Management (TQM) techniques, is being applied to define an oxygen-hydrogen engine.

The baseline design from Phase A/A' studies has been used as a point of departure for trade studies and analyses. Existing STME system models are being enhanced as more detailed module/component characteristics are determined.

Preliminary designs for the open expander, closed expander and gas generator cycles have been prepared, and recommendations for cycle selection made at the Design Concept Review (DCR). As a result of the July '90 DCR, and information subsequently supplied to the Technical Review Team, a gas generator cycle has been selected.

Results of the various Advanced Development Programs (ADPs) for the Advanced Launch System (ALS) have been contributive to this effort.

An active vehicle integration effort is supplying the NASA, Air Force and vehicle contractors with engine parameters and data, and flowing down appropriate vehicle requirements.

Engine design and analysis trade studies are being documented in a data base that has been developed and is being used to organize information. To date, seventy four trade studies have been input to the data base.

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INTRODUCTION

The primary Space Transportation Engine Program (STEP) Phase B objective is to complete a low risk STME design meeting Advanced Launch System (ALS) goals for high reliability, low production cost, and low operational cost propulsion. A further objective is to define program approaches and prepare plans for engine full scale development and validation and for production initiation. Providing the ALS program with timely and accurate engine data and trade assessments is a high priority while accomplishing these goals. This quarterly report provides a brief summary of key technical progress and highlights any issues that need to be resolved to achieve the best program results.

STEP Phase B is structured into three parallel tasks during the 36-month program duration: STME Design; Special Tasks and Analysis; and Phase C/D and E Plans. Do to program replanning the plans preparation task was delayed. The program master schedule is presented in Figure 1.

The preliminary design and substantiating analysis for the LOX/H2 gas generator cycle STME are completed in Task 1. This task is initiated with engine requirements and baseline concept definition. Trade studies required to establish the design are then identified and conducted in the preliminary design subtasks. One preliminary design subtask focuses on engine operability features such as design for ocean recovery and modularity. This subtask feeds into the engine system preliminary design task where the integrated design is completed. Supporting analyses including reliability, safety, engine performance, producibility, operability, and risk are conducted to evaluate and evolve the design. A review of the engine cycle design concepts was conducted.

Task 2, Special Tasks and Analysis, includes assessing engine options, conducting special studies to support Phase C/D and E planning, and ALS program support efforts. Split expander and an open expander cycle LOX/H2 STME designs are evaluated and a baseline configuration established. A series of special studies is conducted to investigate innovative and cost effective methods for conducting full scale development and production. Study results influence Phase C/D and E plans in terms of management structure, information systems, and development/validation approach. Cost estimates and modeling capability are developed to provide visibility for future program costs. The ALS program is supported by upfront participation in propulsion system integration efforts and special environmental and facility study tasks.

To prepare for the next program phase, comprehensive hardware and activities plans are completed in Task 3. These plans include engine requirement and interface definition as well as development, production, and operations plans. Required facilities for the program are identified. An overall management approach and the required tools are also studied and defined. The program life cycle cost is estimated based on the final plans.

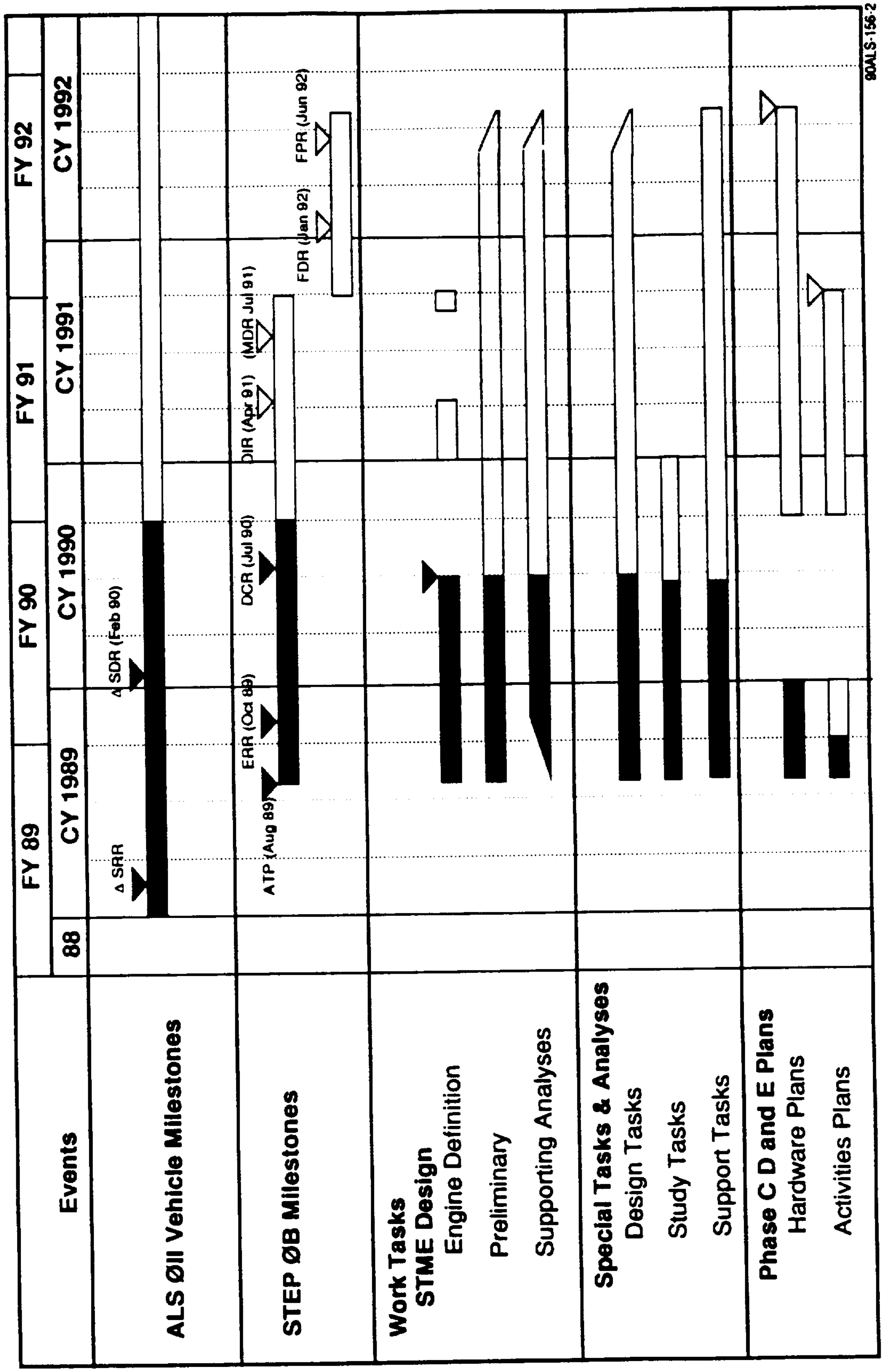

Figure 1. STME Schedule

PROGRESS SUMMARY

Activities since the Design Concept Review (DCR), July 1990, have been concentrating on support of the cycle selection process. Additional analysis was conducted in areas where issues existed with the DCR configuration

A comprehensive evaluation was conducted that identified all discriminators between the Closed Expander (CE) and gas generator (GG) cycles. The information and data resulting from this evaluation was input to the Technical Assessment Team and resulted in the selection of the GG cycle for preliminary design.

The feasibility of GG cycle tank head start has been readdressed since the DCR. This was due to tank head start being identified as a potential discriminator between the GG and CE cycles. With changes to the propellant inlet pressures at start and incorporation of electromechanical actuators in the baseline it was determined that a tank head start was feasible.

A reassessment of the gas cooled nozzle tube wall temperature margin was conducted. A number of system level parameters that affect tube wall temperature were evaluated. In addition, a revised interpretation of the development margin portion of maximum design condition was incorporated. By reducing the engine mixture ratio to 5.5 and the overall turbine pressure ratio from 15 to 7.5 a significant improvement in tube wall temperature margin was achieved.

The oxygen heat exchanger (HEX) design was refined to increase producibility and reduce the size. In support of this effort thermal analysis software was developed based on software written for the Space Shuttle Main Engine heat exchanger. The resulting HEX design incorporates fewer, more machinable channels.

Analyses of film cooling (FC) and mixture ratio (MR) bias affects on combustion chamber wall cooling and engine performance were conducted. Based on the analyses, including FC and MR biasing will not change the engine performance numbers currently quoted.

Figures 2 through 4 present the program task schedules at the subtask level and one level below for clarity. Most of the work on the active work elements is on schedule.

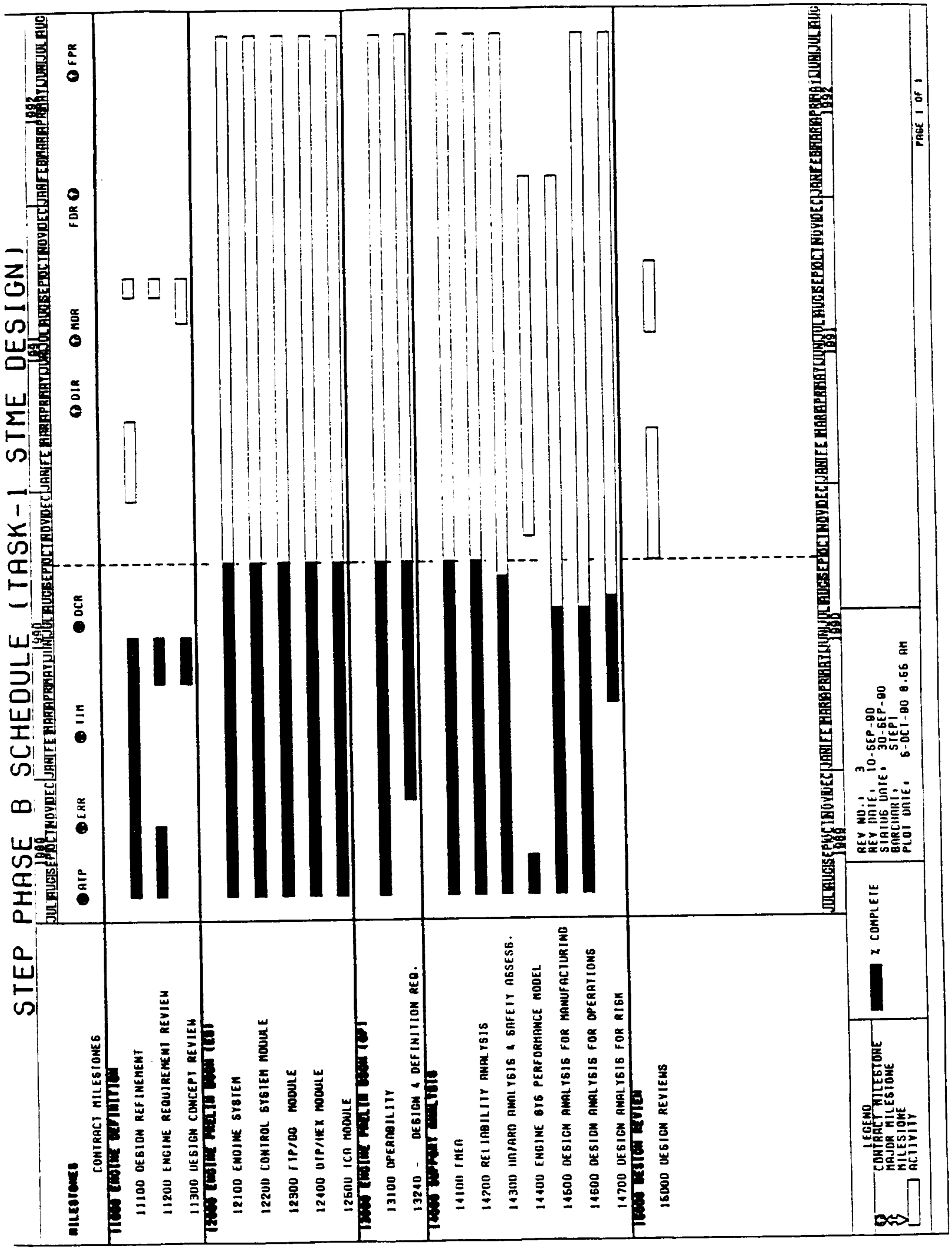

Figure 2. STEP Phase B Schedule (Task - 1 STME Design)

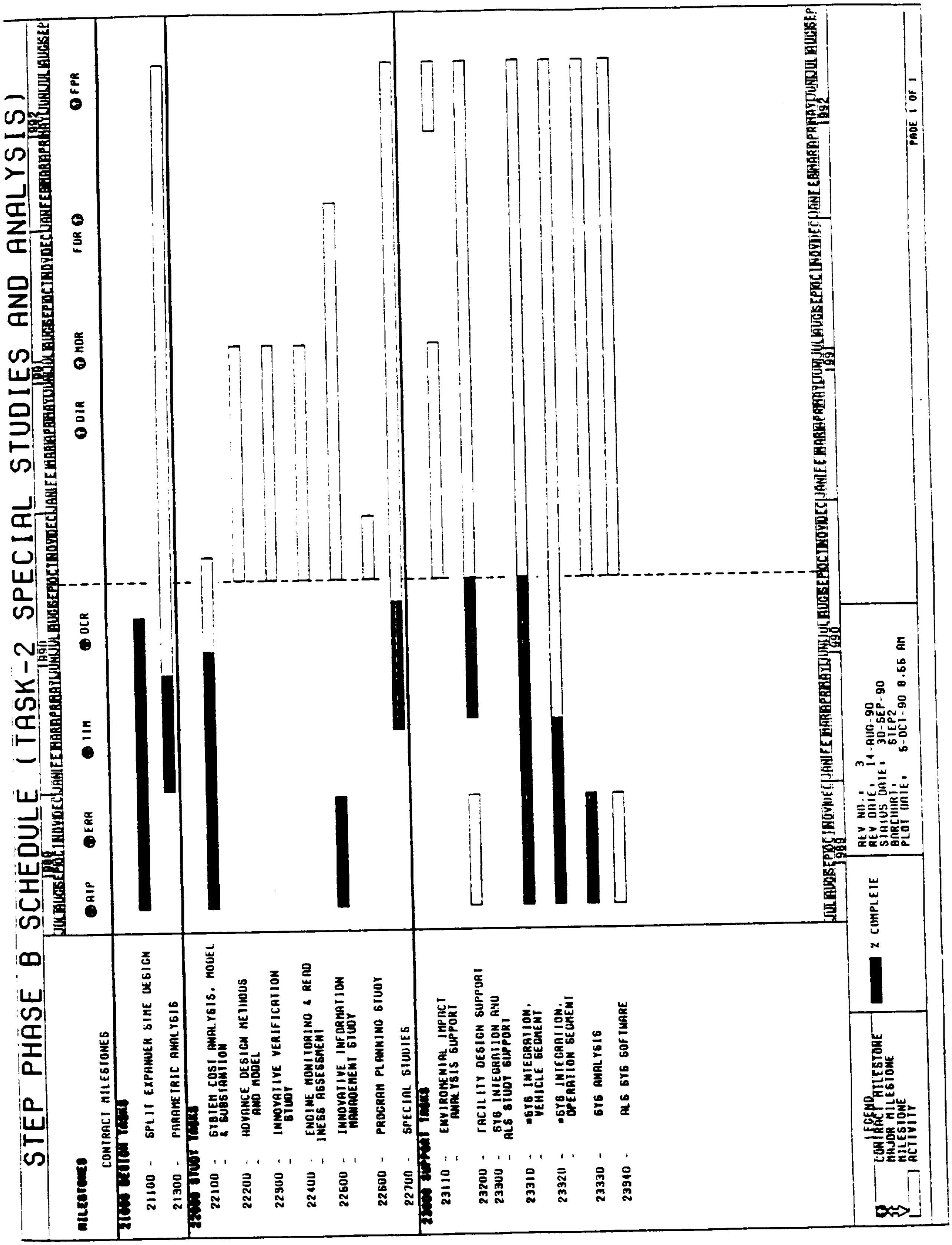

figure 3. STEP Phase B Schedule (Task - 2 Special Studies and Analysis)

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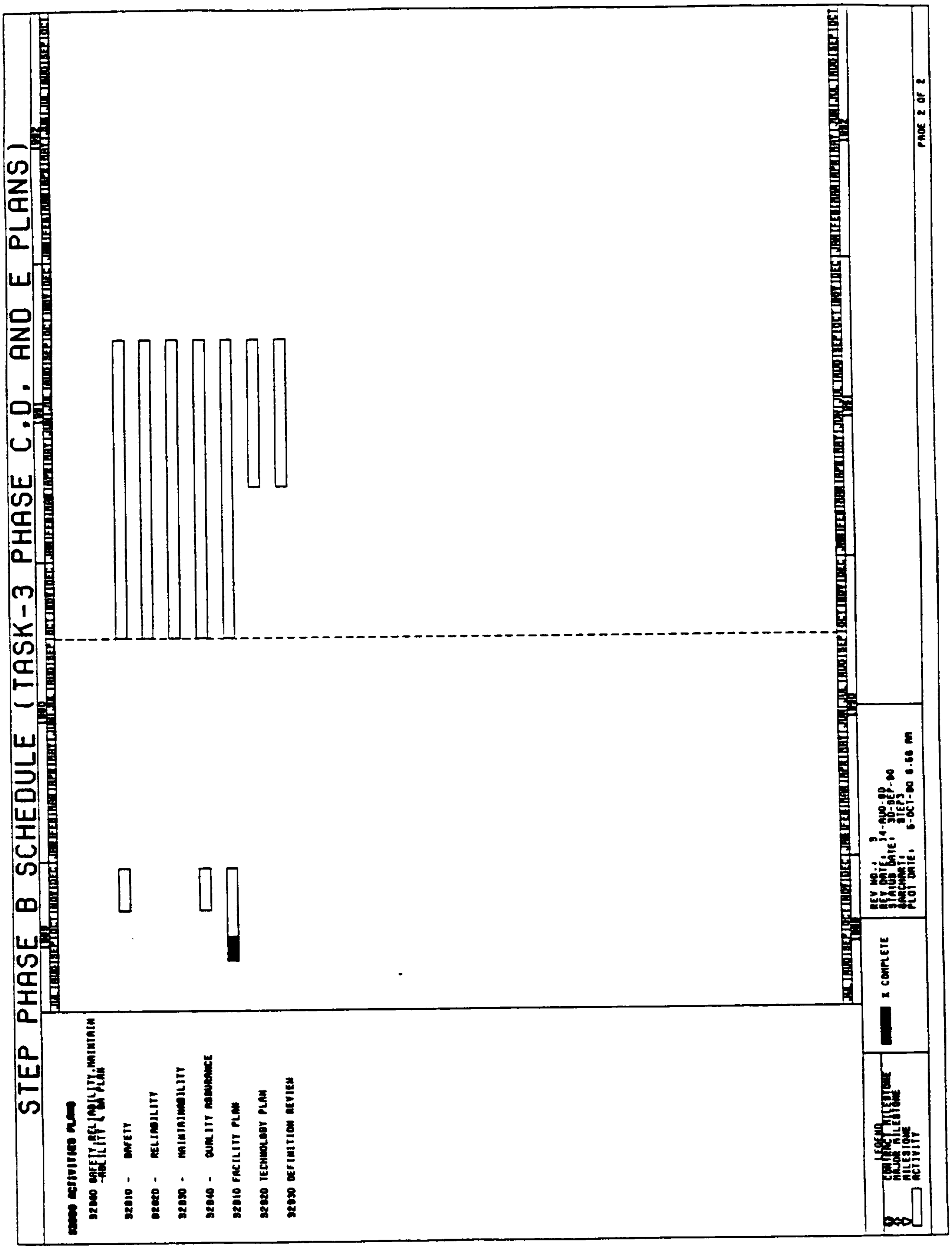


Figure 4. STEP Phase B Schedule (Task - 3 Phase C,D, and E Plans)

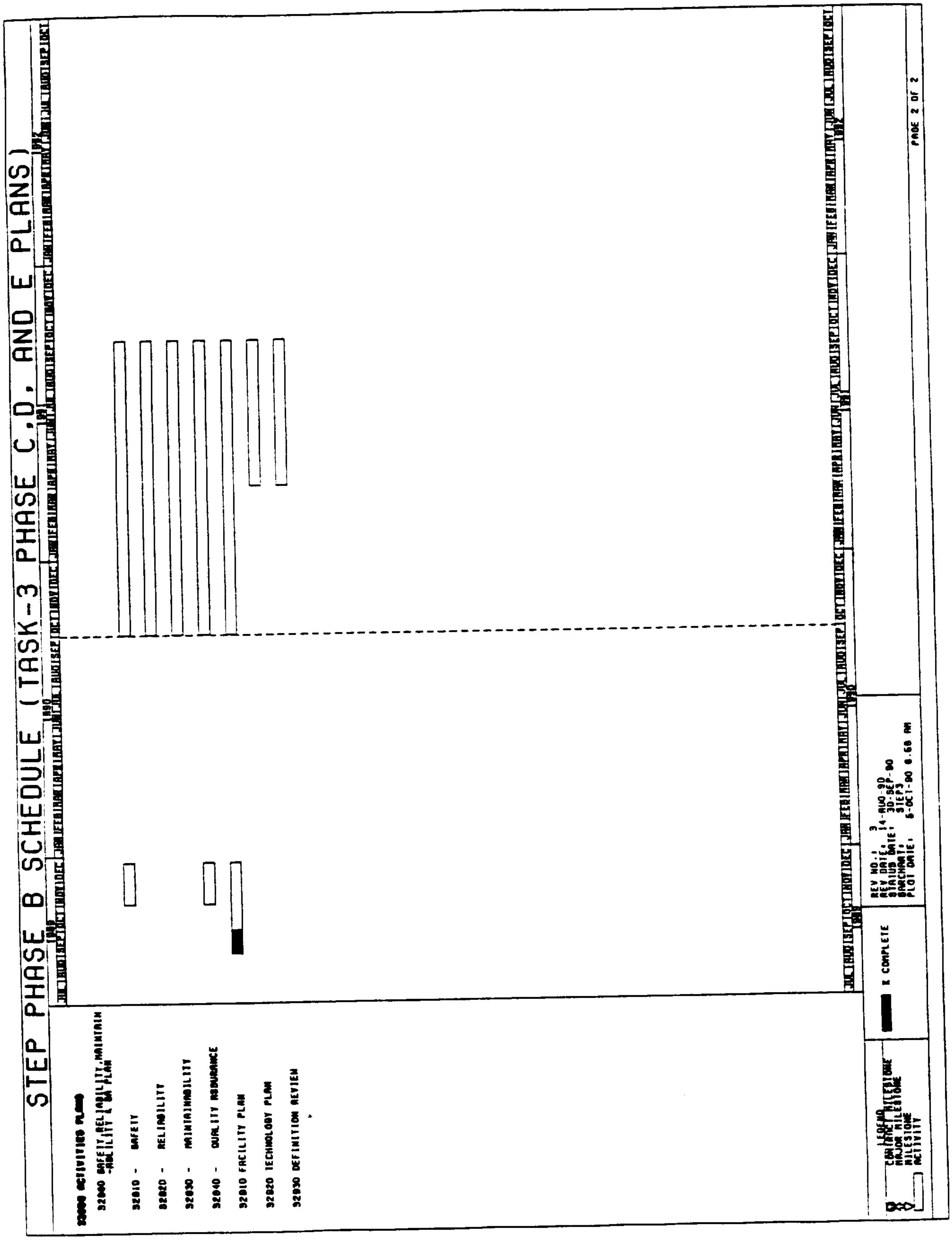


Figure 4. STEP Phase B Schedule (Task - 3 Phase C,D, and E Plans) (Cont.)

TECHNICAL PROGRESS

Task 1: STME Design

Engine Definition

Design Concept Review An evaluation of the various engine configuration concepts was conducted to arrive at the baseline to be used in preliminary design. The evaluation was conducted at two levels. A comparison was conducted between engine cycles to arrive at discriminators based upon the basic characteristics of each cycle. Additionally, a comparison was done at a component level between engine contractors to arrive at the best component configuration for each engine cycle.

After the DCR a technical assessment team was assembled, led by Jan Monk with government and contractor representation. The objective of the team was to recommend an engine cycle and provide supporting rational. The engine cycles evaluated include the open expander, closed expander and gas generator. The selection was based upon a technical assessment of the basic cycle characteristics that are of most important to the Advanced Launch System goals.

The technical assessment teams first task was to arrive at a composite engine configuration for the gas generator and closed expander cycles. The open expander was eliminated early in the selection process. The composite cycles combined the best features of the three engine contractors designs.

Through several telecons and data transmittals between July and August 1990, information was provided assessing the design configurations of all three engine contractors. This data allowed the technical assessment team to develop a composite engine configuration. All subsystems of the engine were addressed with emphasis in those areas that were considered to be discriminators between the cycles.

The composite engine configurations were the basis for additional information provided for comparison purposes between the cycles. The assessment team was then able to use the characteristics and attributes of the composite engines to make a final recommendation. The gas generator cycle was the recommended cycle.

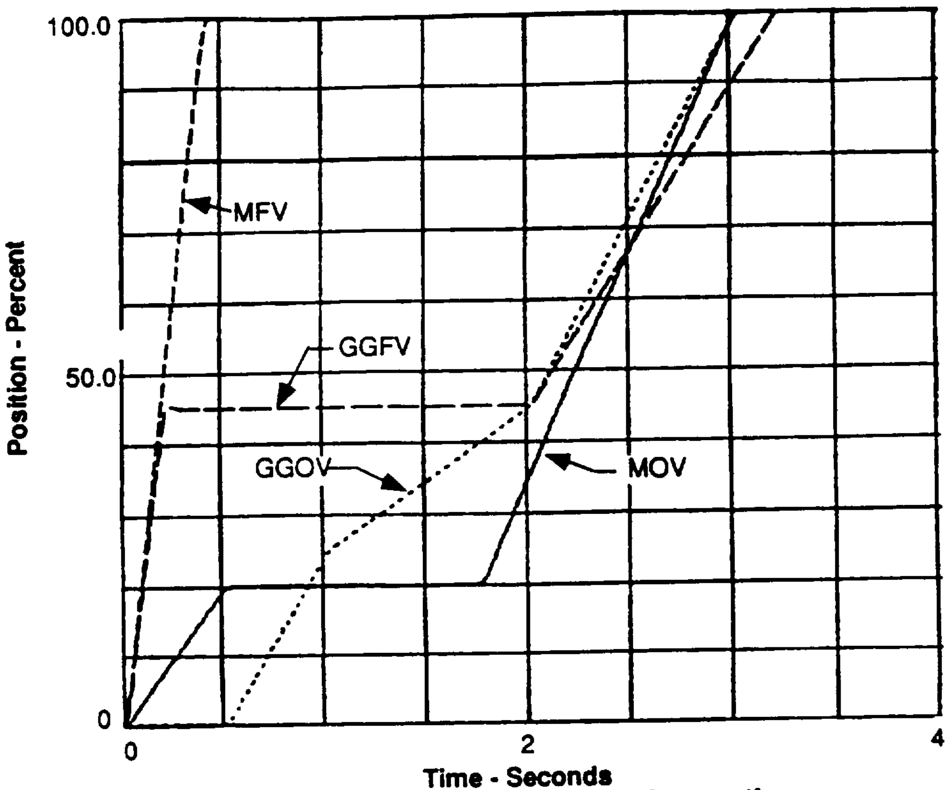
Engine Preliminary Design

Engine Systems This task includes system level analyses as well as system component design and evaluation. The engine system analysis includes all mainstage and transient simulation modeling. A system level structural dynamic analysis is also conducted. The system level design activity includes engine layout definition, envelope and weight assessments. System component design activity includes engine system ducts, mounting brackets and other components not specifically addressed in the other modules. Some of the key trades conducted in this area are included.

Prior to the June Quarterly 1989, an assessment of helium spin, solid propellent gas generator (SPGG) assist, and tank head start was conducted. Originally, the control system was baselined with pneumatically controlled valves. Based on those results, the helium spin and SPGG assisted start had almost identical start characteristics. The tank head start required multiple valve ramp rates and dwell points for the Gas Generator (GG) and Main Valves, and increased fuel inlet pressures to assure Net Positive Suction Head (NPSH) on start and to avoid pump cavitation. There was no sensitivity from vehicle contractors showing spin assist helium consumption to be an issue. There was minimal developmental risk because of considerable past experience with successful gas spin start systems. Moreover, helium spin start assist minimized start variability. The SPGG had an issue relative to pyrotechnics safety, and the additional complexity of valve control for tank head start using pneumatics resulted in increased actuator cost. Therefore, the helium spin start was selected as the lowest risk and lowest cost approach (no vehicle trade factors existed for helium requirement).

Following the Design Concept Review (DCR) in July 1990, helium required for the spin assist start was determined to be a potential discriminator between the GG and Closed Expander (CE) cycles. Since the CE was baselined as tank head start, it was necessary to reevaluate this option for the GG to determine if this indeed was a cycle selection discriminator. The use of electro-mechanical actuators (EMA's) and increased propellant inlet pressures consistent with the current ICD were included in the baseline configuration within which this GG tank head start study was conducted.

The transient study for GG cycle tank head start indicated that satisfactory and repeatable starts could be obtained. It was necessary to provide multiple ramp rates and dwell times for both the Main and GG fuel and LOX valves. Figure 5 shows the valve opening characteristics. In both cases the system would be fuel leading. However, these valve position profiles are well within the capability of EMA's and provide an excellent application for them. The transient analysis indicated a start within 4.5 seconds. Adequate NPSH margin is provided during start. A system with more than 600 lb "warm LOX" is marginal and requires more detailed evaluation. The GG temperature rise was controlled to 74% of the design nominal. The GG and combustion chamber mixture ratio excursions during the start were 0.60 and 5.0, respectively. Tank head start refinements will be studied as the design matures, but no problems are anticipated. A tank head start was determined to be the best option for the GG cycle with the revised baseline configuration. The requirement for linking of the GG valves needs to be reassessed.



Assumptions
Fuel lead
Fuel inlet condition: 57 psi/40°R
LOX inlet condition: 111 psi/182°R

Figure 5. Tank Head Start is Feasible

OTP / HEX Module The oxidizer turbopump heat exchanger module includes the oxidizer turbopump, oxidizer turbine by-pass, and heat exchanger. Trade studies conducted in the oxidizer turbopump component area focus on configuration options, material selection, manufacturing processes and pump performance analyses. Studies performed for the heat exchanger include conceptual design approaches addressing internal and external heat exchangers. Based upon the selected concept, configuration options, manufacturing processes and supporting analyses such as stress and thermal analysis are conducted. These studies are conducted to evolve the baseline design.

Design refinement work has continued on the oxygen heat exchanger (HEX) during the past quarter. The objectives have been to increase the robustness, producibility, and reliability of the design while reducing its cost and weight.

A thermal analysis code was developed to analyze the HEX configuration that was based on a code originally written for the SSME external HEX. The code is capable of using three different oxygen Nusselt number correlations: Dittus-Boetler, Spencer-Rousar, and McCarthy-Wolf. A Dittus-Boetler correlation was used for the hot gas Nusselt number. The baseline configuration was analyzed using the three different correlations. The results, although different, all fell within 10% of the average. It was found that the oxygen properties varied significantly through the exchanger. This is due to the proximity of the HEX operating pressure to the oxygen critical pressure of about 730 psia. In order to mitigate this effect, it was decided that the oxygen pressure be increased to 1000 psia at the inlet. This increases the reliability of the analysis as well as alleviates the unpredictable nature of oxygen near its critical pressure.

The increased detail of the heat transfer analyses provided the basis for design revisions to the HEX. These design revisions included the elimination of the centerbody of the previous baseline in conjunction with the reduction of the HEX inner diameter (ID) to 9.7" to match the ID of the turbine drive crossover duct. This was made possible by rotating the cross section of the channel 90 degrees. A number of channel configurations were analyzed for the revised design with the goal of increasing the producibility of the HEX. Various sizes and numbers of channels were studied.

The design revisions for increasing producibility involved a two step process. First, the channel size was increased to an easily produced size. The length of the HEX was allowed to float depending on the channel size. Next, the number of channels were reduced; this involved an increase again in the channel size to maintain similar flow velocities. The resulting channel configuration was a channel size .120" tall by .060" wide for a total of 150 channels; plenty of material was provided for the land width (.144"). The new configuration allows leeway in the manufacturing of the HEX. It is anticipated that significant cost reductions can now be achieved. Further analysis will be conducted to refine the fabrication process used.

TCA Module This task includes conceptual design definition analyses and trade studies relating to the injector, combustion chamber and nozzle. Efforts involved in this task include concept definition, manufacturing, processes definition, component performance evaluation, and component design refinement. All supporting analyses are included.

Prior to the DCR, an effort was in progress to analyze the STME to identify engine system operating parameters which influence the gas cooling of the nozzle. This initial effort involved a Taguchi study in which a number of parameters were varied to determine their effect on nozzle cooling, engine performance and cost. From this study, it was determined that the most cost effective parameters to adjust (those providing the maximum cooling effect with the minimum performance and hardware cost impacts) were the nozzle attach area ratio, gas generator (GG) temperature, and turbine pressure ratio. Early in the effort, it was concluded that an increase in the nozzle attach area ratio was not a viable candidate for manipulation. This was due to combustion chamber fabrication cost increases associated with attaching at higher area ratios as well as size limitations in current production facilities which limit the combustion chamber to the baseline attach area ratio of 7:1.

Other aspects of the previous effort included an analysis to determine the degree of cooling required for the nozzle. This is dictated by the nozzle tube material structural properties at elevated temperatures. The baseline tube material, INCO 625, exhibits acceptable material properties to a maximum temperature of 1800 °F. (INCO 625 was selected on the basis of its favorable fabrication properties in addition to its relative cost effectiveness as a high temperature alloy.) Accordingly, the nozzle tube wall temperature limit was established at 1800°F for the worst case operating conditions for nozzle cooling. "Worst case conditions" refers to off-design operating conditions derived from the maximum design condition (MDC) definition. These conditions were determined by selecting the combination MDC elements (±3% MR, ±3% thrust, and inlet pressure variations due to flight effects) which, along with the fixed elements of hardware variations and 5% development margin, resulted in turbine drive flow conditions least favorable for nozzle cooling. This "worst case" off-design combination serves as the basis of analyses conducted to determine if the temperature limit is met. The combination of variable elements used was +3% MR, -3% thrust, and high inlet pressures.

Activity since the DCR has been focused on determining specific values of the pertinent nozzle cooling engine system parameters with the objective of minimizing or eliminating any engine performance impacts while bringing the maximum metal temperature to below 1800°F under the worst case conditions. Engine mixture ratio (MR), a system parameter not previously considered, was added to the analysis. By lowering the engine mixture ratio, nozzle cooling is improved due to increased turbine drive flowrate due to greater fuel pump horsepower requirements and the decreased adiabatic flame temperature.

Several different combinations of GG temperature and turbine pressure ratio were analyzed at a MR of 5.5 (this was lowered from the baseline MR of 6.0). Initially, three cases were analyzed. All of them used a turbine pressure ratio of 7.5:1 resulting in a 300 psia turbine exhaust manifold inlet pressure. One case included a nozzle attach area ratio setting of 9:1. The cases were distinguished by GG temperatures which varied between 1450°R and 1550°R. A summary of these results is provided in Table 1. It should be noted that the number of tubes was increased from 540 to 720. The recommendation resulting from this analysis was a GG temperature of 1500°R. This resulted in a tube wall temperature of 1782°F which falls within the established limit of 1800°F.

Analysis conducted since the DCR involved a reevaluation of the worst case off-design operating conditions. The previous MDC definition specified by the ICD defined development margin as 5% of the Rated Power Level (RPL) Parameter value adjustment. Subsequent reevaluation of the development margin resulted in

Table 1. Post DCR Gas Cooled Nozzle Analysis

Parameters	Cases Analyzed		
	1	2	3
Nozzle attach area ratio	7:1	9:1	7:1
GG temperature, °R	1450	1550	1500
Turbine pressure ratio	7.5:1	7.5:1	7.5:1
Number of tubes	720	720	720
MDC nozzle tube wall temperature, °F (using 5% of RPL Parameyer development margin)	**1747**	**1771**	**1782**
	4	5	
Nozzle attach area ratio	7:1	7:1	
GG temperature, °R	1600	1600	
Turbine pressure ratio	7.5:1	7.5:1	
Number of tubes	720	600	
MDC nozzle tube wall temperature, °F (using 5% of Pc development margin)	**1686**	**1790**	

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a proposal to change the definition to 5% of Pc. This definition has since gained acceptance by the propulsion community. With this new definition, the same case previously recommended was analyzed again. The redefinition of Development Margin allowed a return to the nominal GG temperature of 1600°R. Imposing a less severe MDC, this new off-design case yielded a tube wall temperature of 1686°F which is well within the 1800° limit. The corresponding nominal case results in a 1513°F tube wall temperature. These results are also presented in Table 1.

The Advanced Development Program (ADP) Thrust Chamber Assembly effort is in progress of developing an alternate nozzle with a lower cost fabrication approach. Referred to as the "convolute design", an additional system level cooling analysis will be conducted for this design once the concept has matured. For the present nozzle design, the analysis shows sufficient cooling margin is available such that further lower cost cases may be evaluated, i.e. fewer tubes.

Another key analysis conducted within the TCA module area was an analyses of the effects of film cooling (FC) and mixture ratio (MR) bias on wall cooling and performance. Variation in the MR profile over the injector face can be beneficial. A lower MR at the combustor wall with FC along the wall reduces the chances of copper alloy blanching in addition to reducing the metal temperatures. Analysis has shown that the combustion performance impact associated with FC/MR bias is minimal resulting in only a slight increase in Life Cycle Cost due to a lower Isp. Recurring hardware costs are also slightly greater by the cost of drilling holes for the film coolant flow.

A FC/MR bias analysis was conducted with maximum design condition (MDC) MR's of 5.0 at the wall and 6.8 in the inner zone of the injector. It was observed that a sharper drop is incurred in Isp than is incurred in C* when the injector is run at MDC compared to when it is run at nominal conditions. Although Isp does not usually drop faster than C*, it may be explained by the difference in slopes of the two curves at the extreme MR's of this injector.

A configuration with FC only was also evaluated. The advantage of this configuration is that FC by itself is a much more effective thermal barrier for the chamber wall, however, it would be presumably less robust due its total dependence on the condition that the film coolant holes remain unblocked. Operating at the same MDC MR of 5.0 at the wall, a configuration using 4.2% film cooling injected in the outer zone was evaluated. The C* efficiency for this configuration was determined to be 99.60% at nominal conditions. This is only .07% greater than the FC/MR biased configuration. Accordingly, the decrease in robustness associated with this configuration does not appear to be justified.

The analysis predicted that the FC/MR biased configuration will have a C* and Ips which are 99.53% and 99.69%, respectively, of the values for a uniform MR at nominal conditions. These represent losses of approximately .5% in C* and 1.4 seconds in Isp. At MDC, the C* and Isp for the FC/MR biased injector will be 99.51% and 99.29% of the values for a uniform MR injector. The predicted C* efficiency for both of these cases, including mixing and vaporization losses, exceeds the assumed value of 99.00% used for engine performance evaluations, and therefore, FC/MR biasing will not change the engine performance numbers currently quoted.